Reading Page: Traveling Pulses

Any object or particle – your pendulum, or vocal chords, or guitar strings – that moves back and forth, up or down is said to vibrate, or oscillate. A vibration is nothing else than a wiggle, or a pulse. For example, when you wiggle the end of a rope tied to a doorknob up and down, a pulse is created (a disturbance of the particles that make up the rope) that moves along the rope. A pulse that travels is called a traveling pulse or a traveling wave. The pulse you created wiggling your hand, travels along the rope until it reaches the doorknob. We will study later what happens when it reaches the doorknob.

A single disturbance traveling through a medium (rope, water, guitar strings, air, etc) will be called a pulse. Repeating pulses, traveling through a medium will be called waves.

There are three types of waves:
1. mechanical waves
2. electromagnetic waves
3. matter waves

We will first study mechanical waves. A few examples of mechanical traveling pulses/waves are: ripples on the surface of water in a pond created by throwing a rock in it, a plucked guitar string, an oscillating loud speaker cone, the sound of your voice, an earthquake, etc.

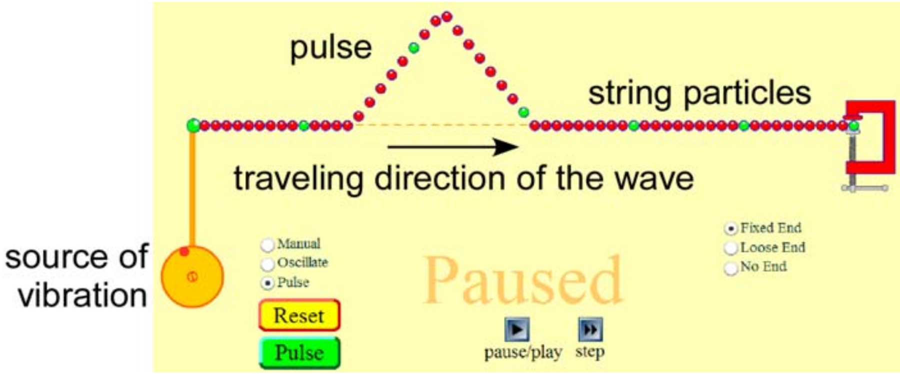
In all these examples the wave disturbance was created by a <u>source</u>: the rock thrown in the pond, the fingers that plucked the string, the sound that comes out of the speaker, the vocal cords moving, the earth collapsing, etc. Once created, this disturbance travels through a medium. The <u>medium</u> of a mechanical wave is the substance through or along which the wave moves, for example: the water, the guitar string, the cone speaker, the air, the earth, etc. As the wave passes through the medium, the particles that make the medium are disturbed from their equilibrium position but this <u>disturbance</u> is an organized motion of the particles of the medium and it travels through the medium with a very well defined <u>speed</u>. This is the speed with which a ripple moves across the surface of the water or a pulse travels along a string, for example.

Mechanical waves are waves that can travel only through a material medium, such as water or air. Light can travel through vacuum and even though it is a wave, it is not a mechanical wave but an electromagnetic one.

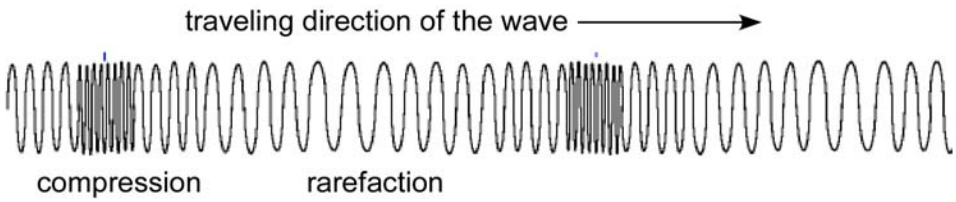
Types of pulse/wave motion:

1. <u>Transverse pulse/wave</u> is a pulse/wave in which the particles in the medium move *perpendicular* to the direction in which the pulse is moving. For example, a wave travels along a string in a horizontal direction while the particles that make up the string oscillate vertically.

Examples of transverse waves include seismic S (secondary) waves, and an oscillating string. A more everyday example would be the wave created by the audience during a football or basketball game.

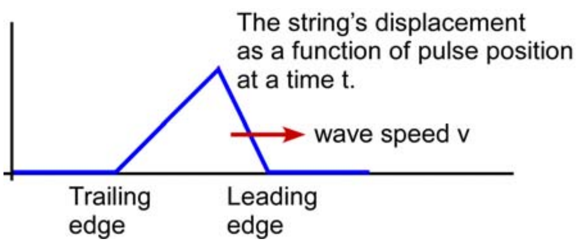


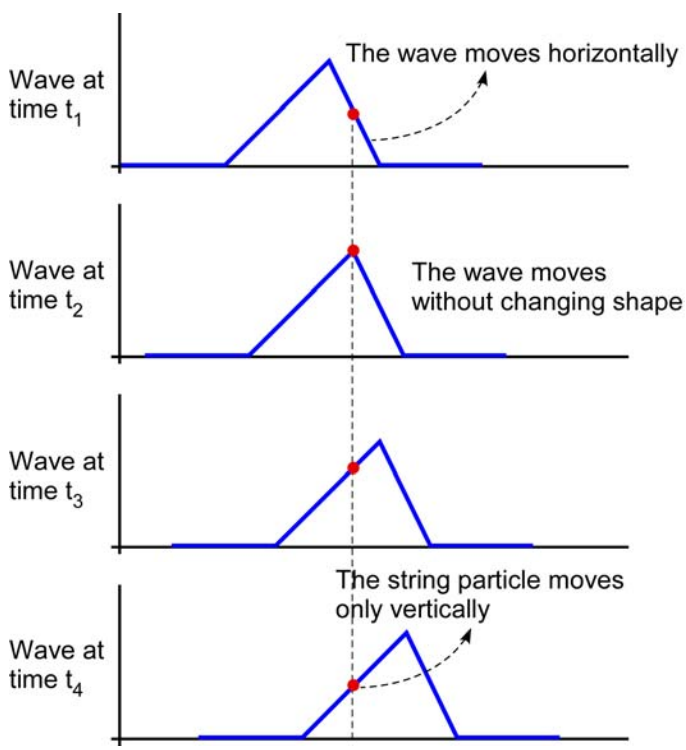
2. In a <u>longitudinal wave</u>, the particles of the medium move *parallel* to the direction in which the wave travels. For example, if you take a very long slinky and stretch it, compress together a few of the coils, and then let go, you get a longitudinal wave (the compression region) traveling along the slinky. Sound waves are examples of longitudinal waves.



How does a mechanical wave travel through a medium?

In answering this question one must be careful to distinguish the motion of the wave from the motion of the particles that make up the medium. The figures below show a transverse pulse traveling to the right across a stretched string.

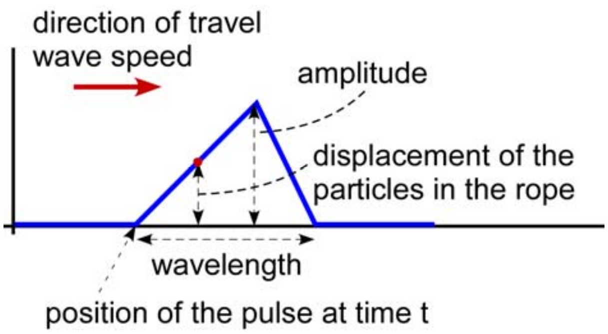




The figure on the left is a “snapshot graph” of the wave and shows the wave’s displacement as a function of position at a single instant in time. For a wave on a string, the snapshot graph is literally a picture of the wave at this instant. The figure on the right shows a sequence of snapshot graphs as the wave continues to move through the string.

The speed of a mechanical wave is dependent on the medium through which it propagates. For example, a pulse/wave sent through a more stretched string moves faster than through a less stretched string. Also, a wave moves faster through a thinner rope than through a thicker rope.

Characteristics of a pulse/wave



Amplitude = the maximum displacement of the particles in the medium from their resting or equilibrium position

Wavelength = the length of the moving pulse

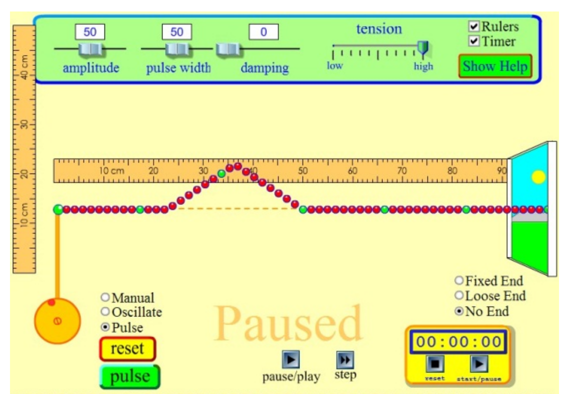
Period = the time it takes a particle in the medium to complete a full oscillation represents the period of the wave, T. The period of a wave also represents the minimum time it takes for a wave to repeat itself, or the time it takes a pulse to pass through a point in the medium.

Frequency = the frequency with which pulses are generated determines the frequency of a wave. Once set, the frequency of a wave does not change as the wave travels away from the source.

What does a wave carry? As we have seen, a wave does not carry matter. The particles of the medium are oscillating up and down for a transversal wave that moves along the horizontal. If we place a standing wooden block at the end of the rope, when a pulse send through the rope reaches the block, it will make it move, or fall over. In order for the wave to do work, it must have energy. Therefore we can state that waves carry energy.

Open the following simulation:
http://phet.colorado.edu/sims/string-wave/string-wave.swf

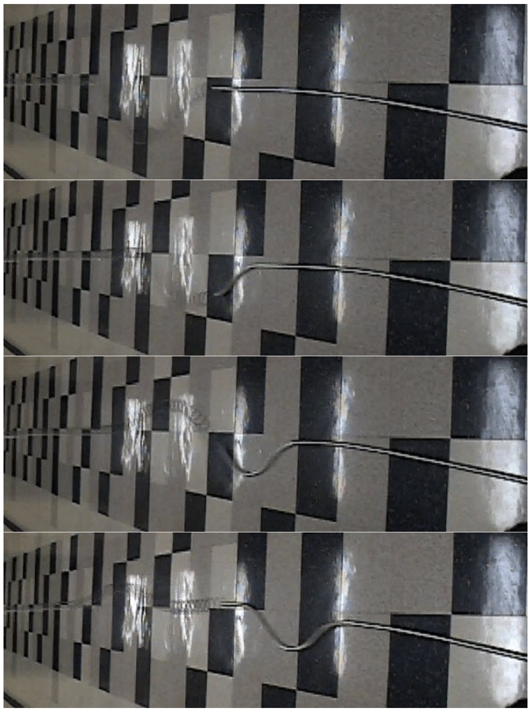
and play with creating pulses in a string.



Additional resources for reading about waves or playing with wave simulations:
http://www.phy.hk/wiki/englishhtm/TwaveA.htm
http://www.acoustics.salford.ac.uk/feschools/waves/wavetypes.htm

Reading Page: Reflection and Transmission of Pulses

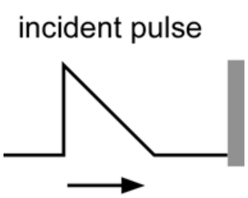
In every experiment run until now, a pulse generated at one end of the slinky traveled to the other end and came back or, in the case of the two slinkies connected together, it traveled from one slinky to the other.



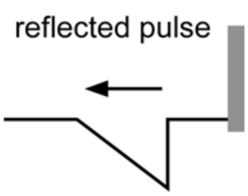
The behavior of a pulse upon reaching the end of a medium is referred to as boundary behavior. How does reflection (coming back) when reaching the end of the slinky affect the pulse? Does reflection of a pulse affect the speed of the pulse? Does reflection of a pulse affect the amplitude of the pulse? Or does reflection affect other properties and characteristics of a pulse's motion? The questions listed here are the types of questions we seek to answer when investigating the boundary behavior of pulses.

Fixed End Reflection

Let's consider a stretched elastic rope. One end of the rope is securely attached to a table leg while the other end is held in the hand by a student, in order to launch pulses into the medium. The end of the rope attached to the table leg is considered a *fixed end*. The table attached to the floor which is attached to the building which is attached to the Earth. When the pulse reaches this fixed end, the last particle of the rope will be unable to move.



When the student introduces a pulse at one end of the rope, the pulse will travel through the rope towards the fixed end of the medium (fixed boundary). This pulse is called the incident pulse since it is incident towards (i.e., approaching) the boundary with the table leg. When the incident pulse reaches the boundary, two things occur:



1. Part of the pulse is reflected and returns towards the other end of the rope. The disturbance which returns to end (where it was generated) after bouncing off the table leg is known as the reflected pulse.
2. Part of the pulse is transmitted to the table leg, causing it to vibrate.

In both cases, energy is carried by the incident, reflected and transmitted wave. Because the vibrations of the table leg are not visible, the energy transmitted to it is usually ignored. We will focus on the reflected pulse. What characteristics and properties could describe the reflected pulse's motion?

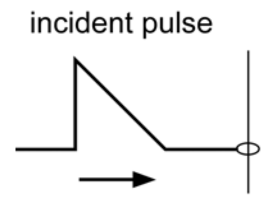
There are several noteworthy observations regarding the pulse reflected off a fixed end. First *the reflected pulse is inverted*. That is, if an upward pulse is incident towards a fixed end boundary, it will reflect and return as a *downward* pulse. Similarly, if a downward pulse is incident towards a fixed end boundary, it will reflect and return as an upward pulse (see figures below).

The inversion of the reflected pulse can be explained by using the concept of a mechanical wave. When the front leg of a pulse reaches the fixed end of a medium ("medium 1", or the end of the rope connected to the table leg), the last particle of medium 1 receives an upward displacement. But this particle is attached to the first particle of the other medium ("medium 2", or the table leg). As the last particle of the rope pulls upwards on the first particle of the table leg, the first particle of the table leg pulls downwards on the last particle of the rope, according to Newton's third law of action-reaction: for every action, there is an equal and opposite reaction. But the upward pull on the first particle of the table leg has little effect due to the large mass of the table. The effect of the downward pull on the last particle of rope (a pull which is in turn transmitted to the other particles in the rope) results in the upward displacement becoming a downward displacement. Thus, the incident upward pulse returns as a reflected downward pulse. It is important to emphasize that it is the heaviness of the table leg relative to the rope which causes the rope to become inverted upon interacting with the table leg.

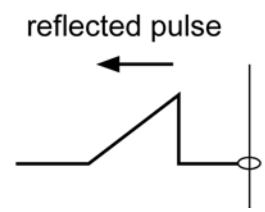
Here is a summary of the characteristics of a pulse reflected from a fixed end:

- The pulse is inverted: an upward incident pulse comes back as a downward reflected pulse
- The speed of the reflected pulse is the same as the speed of the incident pulse: the two pulses are traveling in the same medium
- The wavelength of the reflected pulse is the same as the wavelength of the incident pulse.
- The amplitude of the reflected pulse is less than the amplitude of the incident pulse since some of the energy of the incident pulse was transmitted into the pole at the boundary. The reflected pulse is carrying less energy away from the boundary compared to the energy which the incident pulse carried towards the boundary. Since the amplitude of a pulse is indicative of the energy carried by the pulse, the reflected pulse has smaller amplitude than the incident pulse.

Free End Reflection



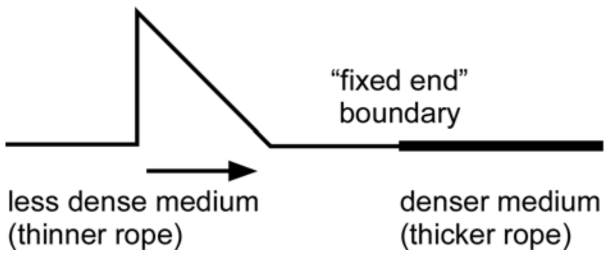
Now let's consider what happens if instead of having one end of the rope connected to the table leg, we actually leave it free to move, by attaching it to a ring which is loosely fit around a pole. This end of the rope is referred to as a *free end*. Because the ring is free to slide on the pole, the end of the rope attached to the ring will also be able to move when a disturbance reaches it.



Let's consider now that the student holding the other end of the rope shakes it and generates a pulse in the rope that propagates toward the free end. When the incident pulse reaches the end of the rope, the last particle of the rope is now free to move and it receives the same upward displacement; but now there is no adjoining particle to pull downward upon the last particle of the rope to cause it to be inverted. Thus the reflected pulse is not inverted. When an upward displaced pulse is incident upon a free end, it returns as an upward displaced pulse after reflection (as shown in the figure at right). And when a downward displaced pulse is incident upon a free end, it returns as a downward displaced pulse after reflection.

Transmission of a Pulse across a Boundary from a Less to a More Dense Medium

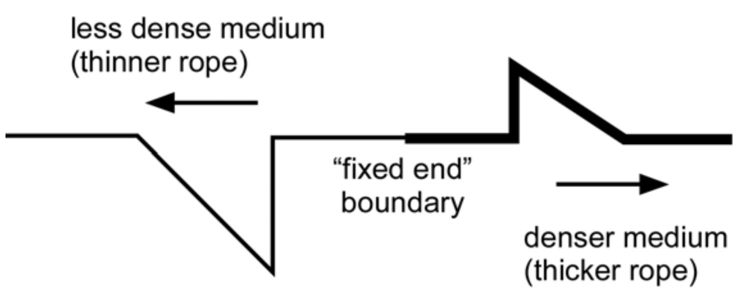
Let's consider that a thin rope is attached to a thick rope, and each end of the two rope system is held down by two students. The student holding the end of the thinner rope produces a pulse. The incident pulse will travel through the thin rope, and reach the boundary between the thin and thick rope. The pulse travels from a thinner rope (less dense medium) to a thicker rope (more dense medium), therefore the boundary can be considered a “fixed end” type of boundary (see figure below).



Upon reaching the boundary, the following behavior will occur:

- Part of the incident pulse is reflected and returns towards the left end of the thin rope: this is the reflected pulse.
- Part of the incident pulse is transmitted into the thick rope: this pulse is known as the transmitted pulse.

The reflected pulse will have the same characteristics as a pulse reflected from a fixed end: will be inverted. The transmitted pulse is not inverted. The thicker rope was at rest prior to the interaction. The first particle of the thick rope receives an upward pull when the incident pulse reaches the boundary. Since the thick rope was originally at rest, an upward pull can do nothing but cause an upward displacement. Because of this, transmitted pulses can never be inverted. The figure below shows the reflected and transmitted pulses.

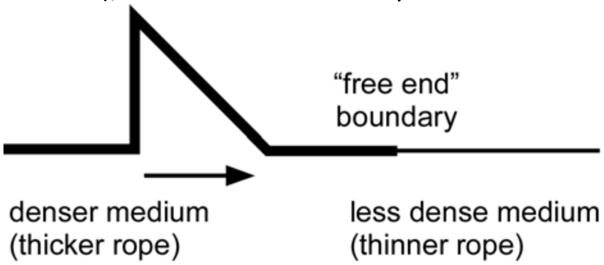


A comparison can be made between the characteristics of the transmitted pulse and those of the reflected pulse.

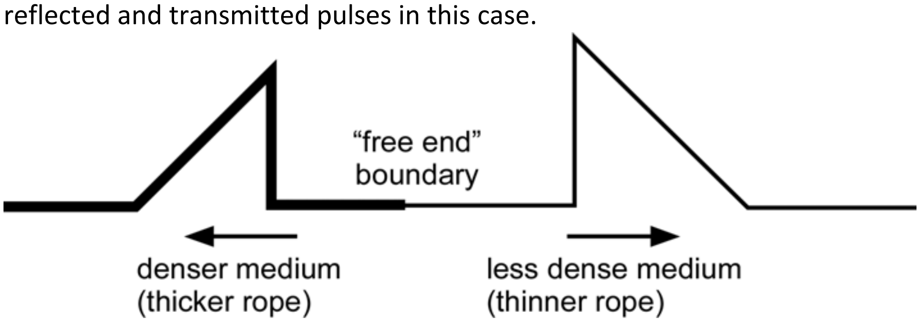
- The transmitted pulse (in the denser medium) is traveling slower than the reflected pulse (in the less dense medium): waves travel faster in less dense medium and slower in denser medium.
- The transmitted pulse (in the denser medium) has a smaller wavelength than the reflected pulse (in the less dense medium).
- The amplitude of the transmitted pulse is smaller than the amplitude of the reflected pulse (or incident pulse).
- The speed and the wavelength of the reflected pulse are the same as the speed and the wavelength of the incident pulse.

Transmission of a Pulse across a Boundary from a Denser to a Less Dense Medium

Let's consider now again that a thin rope is attached to a thick rope, and each end of the two rope system is held down by two students. The student holding the end of the thicker rope now produces a pulse. The incident pulse will travel through the thick rope, and reach the boundary between the thick and thin rope. The pulse travels from a thicker rope (more dense medium) to a thinner rope (less dense medium), therefore the boundary can be considered a “free end” type of boundary (see figure below).



Once again there will be a reflected pulse and a transmitted pulse at the boundary. The reflected pulse will have the same characteristics as the pulse reflected from a free end: it will not be inverted. Similarly, the transmitted pulse is not inverted (as is always the case). Since the incident pulse is in the denser medium, when it reaches the boundary, the first particle of the less dense medium does not have sufficient mass to overpower the last particle of the more dense medium. The result is that an upward displaced pulse incident towards the boundary will reflect as an upward displaced pulse. The figure below shows the reflected and transmitted pulses in this case.



A comparison can be made between the characteristics of the transmitted pulse and those of the reflected pulse.

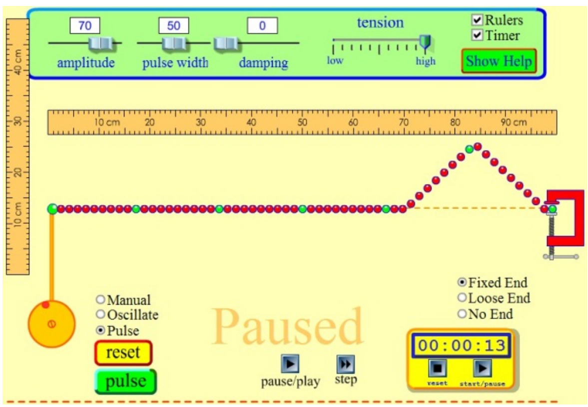
- The transmitted pulse (in the thinner rope) is traveling faster than the reflected pulse (in the thicker rope).
- The transmitted pulse (in the thinner rope) has a larger wavelength than the reflected pulse (in the thicker rope).
- The speed and the wavelength of the reflected pulse are the same as the speed and the wavelength of the incident pulse.

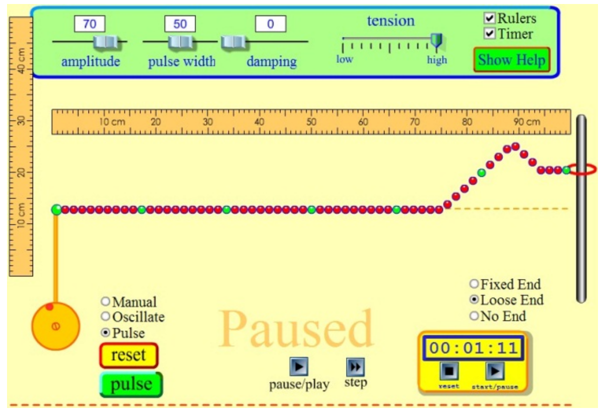
The behavior of pulse propagating in ropes and reaching a boundary can be summarized as follows:

- The pulse speed is always greatest in the least dense rope.
- The wavelength of the pulse is always greatest in the least dense rope.
- The frequency of the pulse is not altered by crossing a boundary.
- A pulse becomes inverted when reflected from a fixed end, or when is heading towards a denser boundary.
- The amplitude of the incident pulse is always greater than the amplitude of the reflected pulse.

Open the simulation at:

http://phet.colorado.edu/sims/string-wave/string-wave.swf
and play with different pulses reflecting from a fixed or free end.

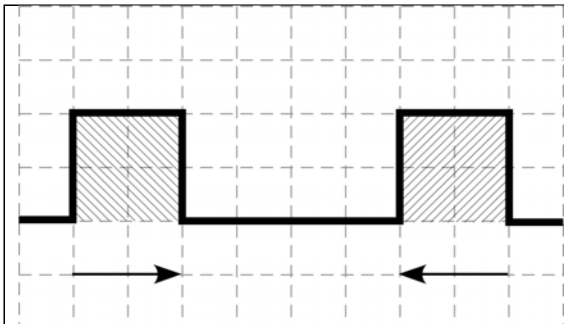
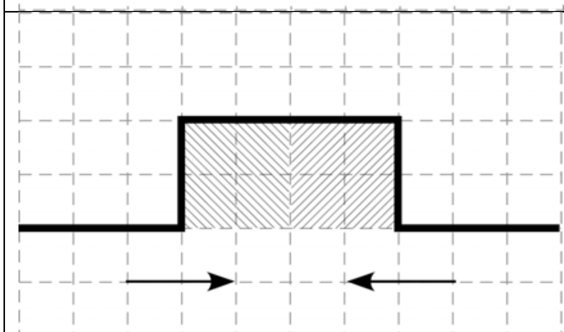
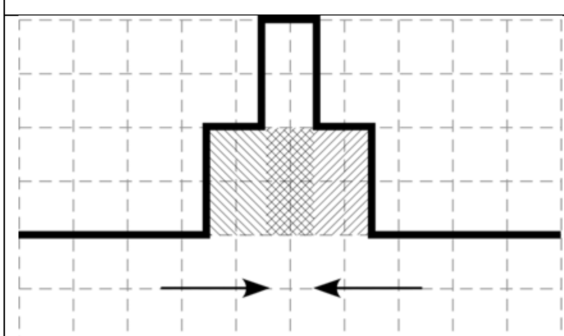


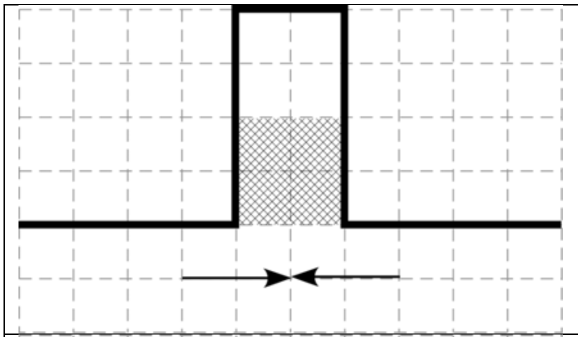
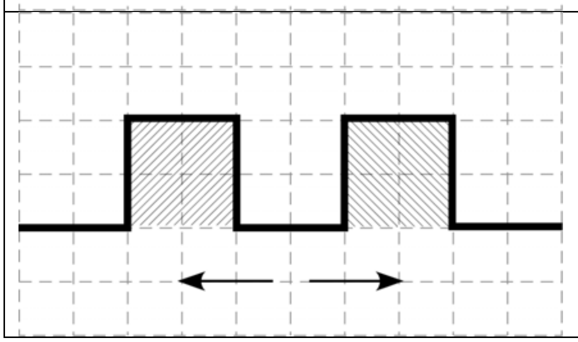


Reading Page: Pulse Propagation and Interference

What happens when two pulses meet while they travel through the same medium? What effect will the meeting of the pulses have upon the medium? Will the two pulses bounce off each other upon meeting (much like two balls would) or will the two pulses pass through each other? The answer to these questions is provided by the study of the interference of pulses/waves phenomena.

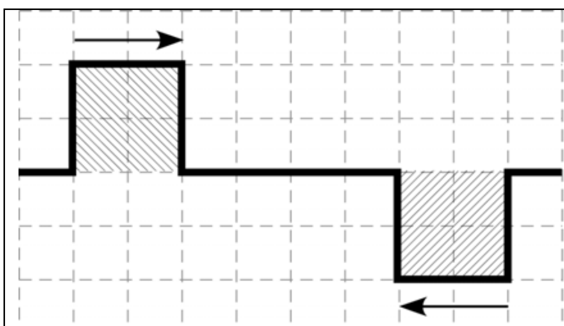
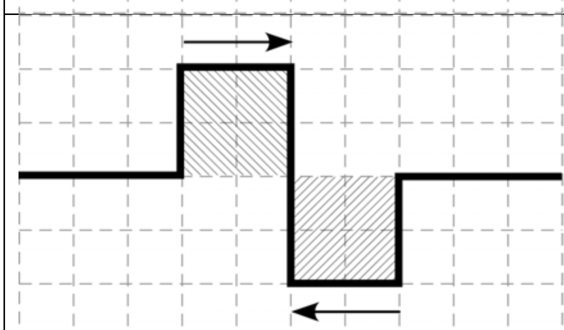
Wave/pulse interference is the phenomenon which occurs when two waves meet while traveling along the same medium. When two waves/pulses interfere, the medium takes on a shape which results from the total/net effect of the two individual pulses upon the particles of the medium. The figures below show what happens to the particles of the medium before and during the interference of two pulses traveling in opposite directions. The individual pulses are drawn in green and blue and the resulting displacement of the medium is drawn in red.

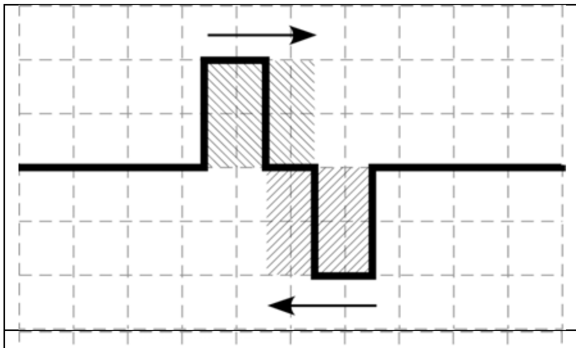
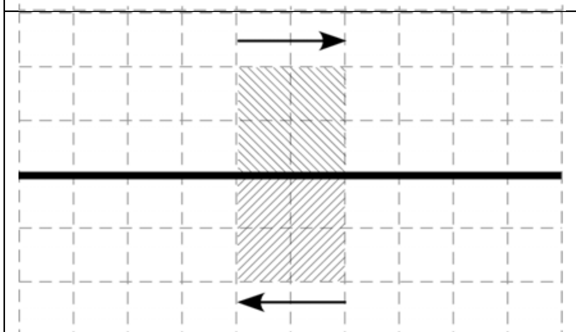
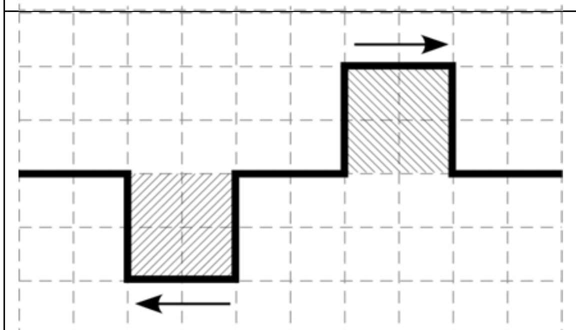
	Let's consider two pulses of the same amplitude traveling in opposite directions (toward each other) along the same medium (rope or slinky for example). Each pulse has amplitude (maximum displacement of the particles of the medium) of 2 units.
	As the two pulses move towards each other, there will eventually be a moment in time when the front of the two waves will reach the same particle in the medium at the same time. The shape of the medium (rope in this case) will be given by the superposition of the two pulses: the total displacement of the particles of the medium will be given by the sum of the displacement due to each pulse.
	In this case, the two pulses overlap but not completely. In the region of overlap, the displacement of the particles of the medium is larger than in the other regions: the displacement is 4 units (2 units from left pulse + 2 units from right pulse). The black, thick line represents the resulting pulse as well as the shape of the medium (rope). The resulting pulse has amplitude that is bigger than the amplitude of the individual pulses.

	At this particular moment (an instant) in time the two pulses are completely overlapped. In the region of overlap, the displacement of the particles of the medium is 4 units and the shape of the medium (rope) and the resulting pulse is given by the black, thick line.
	After interfering, the two pulses continue to travel without any change to their characteristics.

This example shows *constructive interference*: constructive interference is a type of interference can occur when the two interfering waves have a displacement in the *same direction*. In this case, both waves have an upward displacement; consequently, the medium has an upward displacement which is greater than the displacement of the individual interfering pulses. Constructive interference is also observed when both interfering waves are displaced downward.

Destructive interference is a type of interference that occurs where two interfering pulses with displacements in opposite directions, overlap.

	The figure shows an upward pulse with a maximum displacement of +2 units that moves to the right and meets a downward pulse with a maximum displacement of -2 units that moves to the left.
	When the two pulses start overlapping, the resulting pulse has a displacement that is the sum of the displacement due to each pulse. The shape of the resulting pulse is represented by the thick black line.

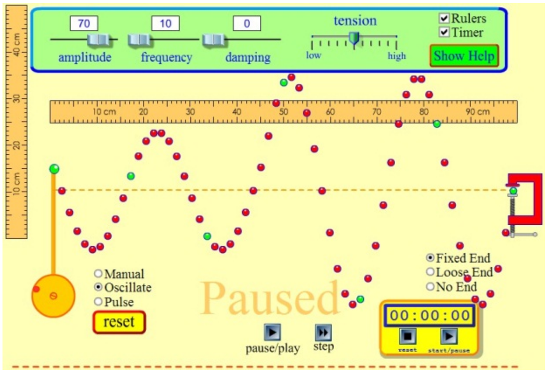
	When the two pulses superimpose, the shape of the resultant pulse (the displacement of the particles of the medium) is given by the algebraic sum of the displacement of the two pulses. In the region of overlap, the displacement is zero: (+2 units for the left pulse) + (-2 units for the right pulse) = 0 units of displacement.
	At the instant in time that the two pulses completely overlap, the result is that the two pulses completely destroy each other. At the instant of complete overlap, there is no resulting displacement of the particles of the medium. It looks like the two pulses disappeared, or destroyed each other.
	In the next moment though, the two pulses continue on their way without having any of their characteristics changed due to their interference.

When two balls meet or two football players meet, they might crash and bounce off each other or might crash and come to a stop. When two pulses traveling along a medium meet, the individual pulses are not altered and they are not deviated from their path. The two pulses will meet, produce a net resulting shape of the medium, and then continue on doing what they were doing before the interference.

To determine the shape of the resultant pulse when to pulses/waves interfere, one must apply the principle of superposition:

When two waves interfere, the resulting displacement of the medium at any location is the algebraic sum of the displacements of the individual waves at that same location.

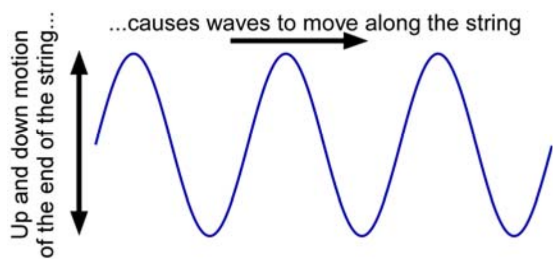
Open the simulation at: http://phet.colorado.edu/sims/string-wave/string-wave.swf and choosing the fixed end, send oscillations through the string. Observe what happens when the reflected oscillations meet the incident ones.



Reading Page: Traveling Waves/Repeating Pulses

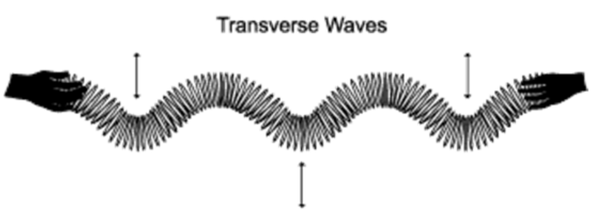
What are waves, what produces a wave, how do waves travel, what do waves transfer, what does the wave depend on, and so on, are questions we would like to answer.

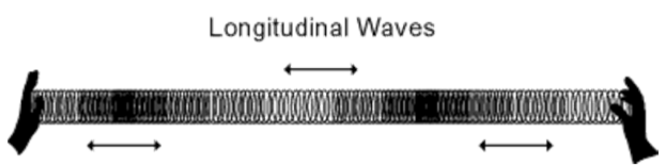
Up until now we have created pulses in a slinky or in a rope by moving our hand, holding one end of the rope or slinky, up and down or left to right. If we repeat the up and down or the left to right motion of our hand, several pulses are sent along the rope or slinky. This resulting propagating disturbance, that has a repetitive pattern, is called a wave. *In general, any disturbance that propagates can be called a wave.*



When one studies waves, it is very important to realize that there are two things that one studies simultaneously: the motion (oscillation) of the medium in which the wave travels, and the traveling of the wave itself.

There are two main types of waves: transverse and longitudinal waves. These two types of waves are distinguished by the relationship between the direction of the oscillation of the medium in which the wave travels and the direction of the propagation of the wave. In a *transverse* wave the particles of the medium oscillate perpendicular (or transverse) to the direction of propagation. A good example of a transverse wave is a wave on a string fixed at one end. When the free end of the string is moved up and down, a wave is set to travel through the string.

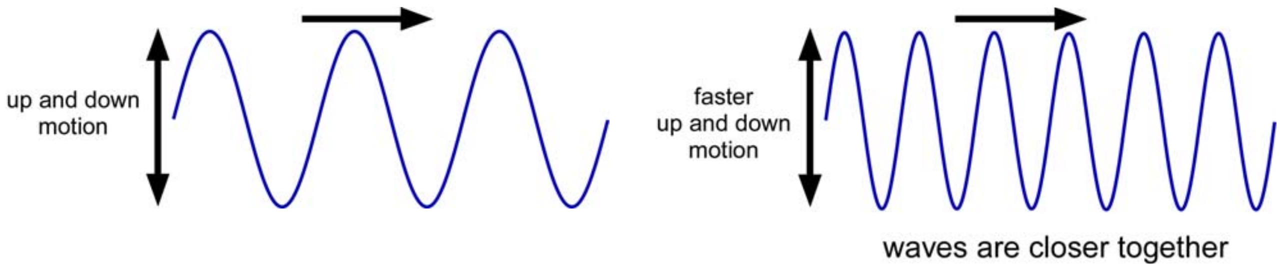




(Pictures from http://swift.sonoma.edu/education/slinky_booklet/index.html)

The other main type of wave is a *longitudinal* wave in which the particles of the medium oscillate along the same line as the direction of propagation. If you take a very long slinky and stretch it, compress together a few of the coils, and then let go, you get a longitudinal wave (the compression region) traveling along the slinky.

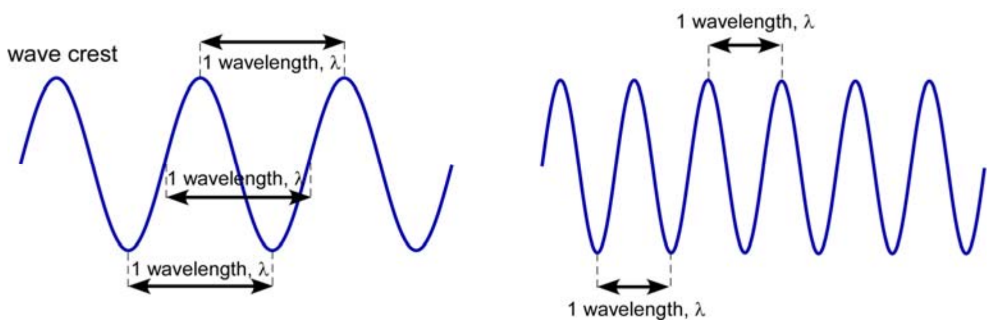
The second thing you might have noticed is that the faster you move your hand up and down to create the waves, the closer together they are.



For waves that are closer together, more of them will pass a given point in a given time than if they are farther apart waves. In order to keep track of the size of waves, how close together they are, or how fast they pass a given point (move), we must define a few characteristics of the waves. The main characteristics of waves are related to the repeating motion (oscillating motion) of the medium.

Frequency = the number of wavelengths that pass a given point per second. The frequency of a wave, f, will be given by the frequency of the wave source, e.g., the frequency of the oscillations of the medium (or how fast you wiggle the end of the slinky or rope).

Wavelength = the distance in which a wave repeats itself. If you wiggle the string faster, a wave crest travels a shorter distance before a new wave crest is ready to move in, therefore the wavelength is smaller.



Period = the time it takes a particle in the medium to complete a full oscillation represents the period of the wave, T. The period of a wave also represents the minimum time it takes for a wave to repeat itself.

The period and frequency are related through:

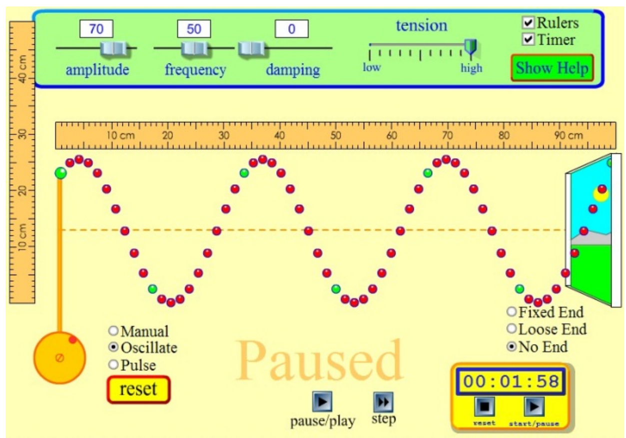
$$T = \frac{1}{f}$$

Wave speed = how fast a wave travels through a medium. This speed can be calculated as the distance the wave travels before it repeats (the wavelength) divided by the time it takes the wave to repeat (the period).

Amplitude = the maximum displacement of the particles of the medium from equilibrium.

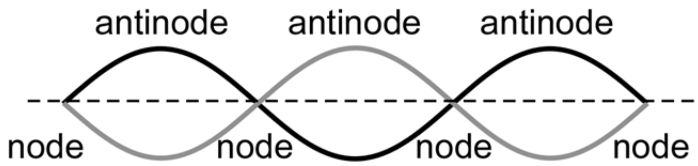
Waves are said to transport energy. As a disturbance/wave moves through a medium, energy is being transported from one end of the medium to the other. For example, in a longitudinal slinky wave, a person transfers energy to the first coil by doing work on it. The first coil receives a large amount of energy which it transfers to the second coil. When the first coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. Now the second coil has a larger amount of energy which it transfers to the third coil. When the second coil returns to its original position, it possesses the same amount of energy as it had before it was displaced. The third coil has received the energy of the second coil. This process of energy transfer continues as each coil interacts with its neighbor. In this manner, energy is transported from one end of the slinky to the other, from its source to another location, without matter being transferred.

Open the simulation
http://phet.colorado.edu/sims/string-wave/string-wave.swf
and use "oscillations" to create waves. Study wave reflection from a fixed and free end and wave interference. You can adjust the amplitude, frequency and tension in the string to see how these parameters affect the wave.



Reading Page: Standing Waves

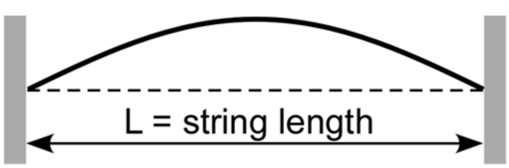
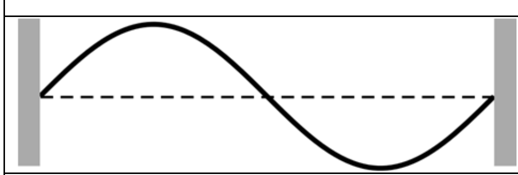
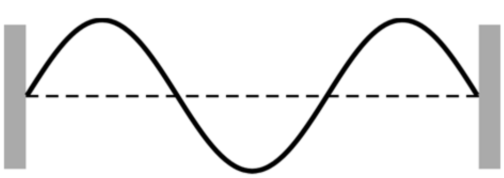
One of the most important consequences of the superposition of waves occurs when a wave and its reflection travels through a medium, or two identical waves travel in opposite directions in the same medium. Under specific conditions, these two waves, traveling in opposite directions, combine to produce what is called a standing wave. Standing waves can be set up in a stretched string by connecting one end of the string to a stationary vibrating object. Traveling waves will reflect back from the fixed end and for very specific frequencies, the wave will appear to stand still – and thus its name of standing wave. A standing wave is a wave that oscillates in time but is fixed in its spatial location. Standing waves contain nodes, where no oscillation occurs and other positions where the oscillation of the medium has maximum amplitude, called antinodes.

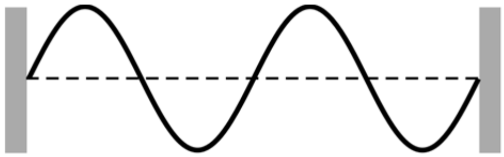


The picture above shows a standing wave pattern in a string fixed at both ends. A node occurs where the two traveling waves always have the same magnitude of displacement but the opposite sign (they are out of phase), so the net displacement is zero at that point. There is no motion in the string at the nodes, but midway between two adjacent nodes, at an antinode, the string vibrates with the largest amplitude.

Standing Waves on a String

To establish a standing wave on a string with fixed ends, such as a guitar string, each fixed end must be a node. Therefore, the only standing waves that can be established on such a string are those that meet the condition of having nodes at the fixed ends. The longest wavelength of a standing wave that will satisfy these conditions is called the fundamental mode (when thinking in terms of wavelength) or the first harmonic (when thinking in terms of frequency).

	In this case, the length of the string corresponds to half the wavelength: $L = \frac{\lambda_1}{2} \Rightarrow \lambda_1 = 2L$ and the string has one antinode. This is called the fundamental frequency, or the first harmonic.
	In this case, the length of the string corresponds to one wavelength: $L = \lambda_2 \Rightarrow \lambda_2 = L$ and the string has two antinodes. (second harmonic)
	In this case, the length of the string corresponds to one and a half wavelength: $L = \frac{3}{2}\lambda_3 \Rightarrow \lambda_3 = \frac{2}{3}L$ and the string has three antinodes.(third harmonic)

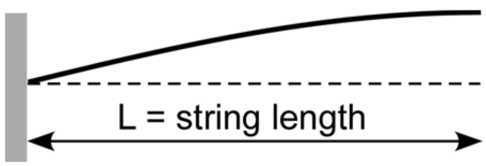
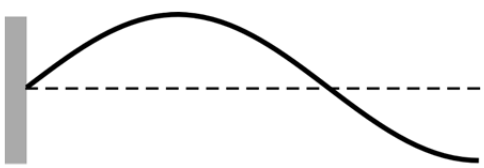
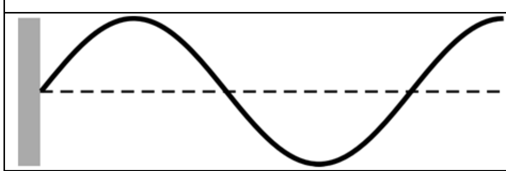
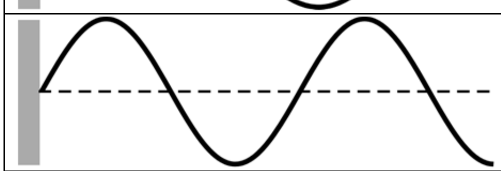
	In this case, the length of the string corresponds to two wavelengths: $L = 2\lambda_4 \Rightarrow \lambda_4 = \frac{L}{2}$ and the string has four antinodes. (fourth harmonic)

And so on…

For each one of the harmonics there is a corresponding frequency which can be calculated as: $f = \frac{v}{\lambda}$, where λ corresponds to a particular mode of vibration. For example, the corresponding frequency of the first harmonic is found to be $f_1 = \frac{v}{\lambda_1} \Rightarrow f_1 = \frac{v}{2L}$. Continuing to examine the different modes possible on strings with fixed ends shows that frequencies can be determined by

$$f_n = nf_1 \text{ where } n = 1, 2, 3, \ldots$$

In the case of a string fixed at one end only, the only standing waves that can be established are ones that have a node at the fixed end and an antinode at the free end.

	In this case, the length of the string corresponds to a quarter of the wavelength: $L = \frac{\lambda_1}{4} \Rightarrow \lambda_1 = 4L$ and the string has one antinode (at the free end) and a node at the fixed end.
	In this case, the length of the string corresponds to 3/4 of wavelength: $L = \frac{3}{4}\lambda_2 \Rightarrow \lambda_2 = \frac{4}{3}L$ and the string has two antinodes and two nodes.
	In this case, the length of the string corresponds to 5/4 wavelength: $L = \frac{5}{4}\lambda_3 \Rightarrow \lambda_3 = \frac{4}{5}L$ and the string has three antinodes.
	In this case, the length of the string corresponds to 7/4 wavelengths: $L = \frac{7}{4}\lambda_4 \Rightarrow \lambda_4 = \frac{4}{7}L$ and the string has four antinodes.

And so on…

For each one of the harmonics there is a corresponding frequency which can be calculated as: $f = \frac{v}{\lambda}$, where λ corresponds to a particular mode of vibration. For example, the corresponding frequency of the first harmonic is found to be $f_1 = \frac{v}{\lambda_1} \Rightarrow f_1 = \frac{v}{4L}$. For the second harmonic, $f_2 = \frac{v}{\lambda_2} \Rightarrow f_2 = \frac{3v}{4L}$. As one can see, the second harmonic is 3 times the first harmonic. That is why, instead of calling it the second harmonic, we will call it the third harmonic. $\Rightarrow f_3 = \frac{v}{\lambda_3} \Rightarrow f_3 = 3\frac{v}{4L} = 3f_1$. Continuing to examine the different modes possible on strings with one fixed end and one free end shows that frequency of any harmonic can be determined by

$$f_n = nf_1 \text{ where } n = 1, 3, 5, \ldots$$

The even numbered harmonics for strings fixed at one end only do not exist, only odd numbered harmonics.

Beats

The superposition of waves of different frequencies gives rise to the phenomenon called beats. These beats appear as a regular fluctuation in the intensity of the wave that results from the superposition. This variation in intensity results from a variation in the amplitude of the resultant wave. The frequency of the successive intensity maxima is called the beat frequency. Two waves of frequencies f_1 and f_2 would produce a beat frequency equal to the difference between them

$$f_{beats} = |f_1 - f_2|$$

Beats are often heard when two guitar strings are played at the same time and are often used to tune musical instruments to the desired frequency.

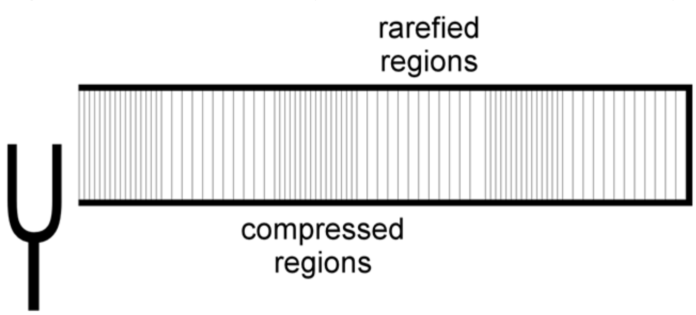
Reading Page: Sound Waves

Sound and music are parts of our everyday experience, and our ears allow us to detect sound the same way our eyes detect light. Sound is a wave which is created by vibrating objects. Sound also needs a medium to propagate from one location to another.

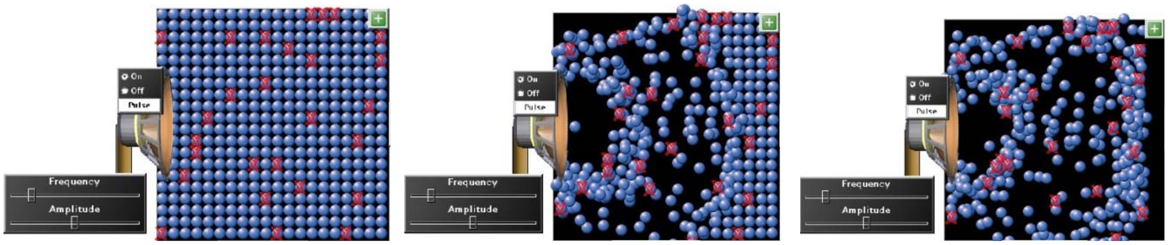
A sound wave is very similar to a longitudinal wave in a slinky. First, both need a medium in which the disturbance is carried from one location to another. For the longitudinal wave, the coils of the slinky are the medium, for sound, the air through which it travels (for example) is the medium. Of course, sound can travel in different media too, for example water, steel, glass, etc. Second, there is a source of the wave, such as a vibrating object capable of disturbing the first particle of the medium. For the longitudinal waves in the slinky, the source of the traveling disturbance is the coils pushed together. For sound, a vibrating object can create the disturbance, for example the vocal chords of a person, a vibrating string and sound board of a guitar or violin, the vibrating tines of a tuning fork, or the vibrating diaphragm of a radio speaker.

Third, both waves are transported from one location to another by means of particle-to-particle interaction. In the slinky, the coils interact with each other, for sound, the air particles interact with each other. If the sound wave is moving through air, then as one air particle is displaced from its equilibrium position, it exerts a push or pull on its nearest neighbors, causing them to be displaced from their equilibrium position. This particle interaction continues throughout the entire medium, with each particle interacting and causing a disturbance of its nearest neighbors. Since a sound wave is a disturbance which is transported through a medium via the mechanism of particle-to-particle interaction, a sound wave is a mechanical wave. One can demonstrate this by placing a ringing bell in a jar and evacuate the air inside the jar. Once air is removed from the jar, the sound of the ringing bell can no longer be heard. The clapper is seen striking the bell; but the sound which it produces cannot be heard because there are no particles inside of the jar to transport the disturbance through the vacuum. Sound is a mechanical wave and cannot travel through a vacuum.

Sound waves in air (and any fluid medium) are longitudinal waves because particles of the medium through which the sound is transported vibrate parallel to the direction which the sound wave moves. Because of the longitudinal motion of the air particles, there are regions in the air where the air particles are compressed together and other regions where the air particles are spread apart. These regions are known as compressions and rarefactions respectively. The compressions are regions of high air pressure while the rarefactions are regions of low air pressure. The diagram below depicts a sound wave created by a tuning fork and propagated through the air in an open tube. The compressed and rarefied regions are labeled.



Since a sound wave consists of a repeating pattern of high pressure and low pressure regions moving through a medium, it is sometimes referred to as a pressure wave. If a detector, whether it be the human ear or a man-made instrument, is used to detect a sound wave, it would detect fluctuations in pressure as the sound wave impinges upon the detecting device. For a better visualization of a sound wave, open the simulation http://phet.colorado.edu/new/simulations/sims.php?sim=Wave_Interference
and choose "sound". Regions of high and low pressure will be visible.



Pitch and Frequency

A sound wave, like any other wave, is introduced into a medium by a vibrating object. The vibrating object is the source of the disturbance which moves through the medium. The vibrating object which creates the disturbance could be the vocal chords of a person, the vibrating string and sound board of a guitar or violin, the vibrating tines of a tuning fork, or the vibrating diaphragm of a radio speaker. Regardless of what vibrating object is creating the sound wave, the particles of the medium through which the sound moves are vibrating in a back and forth motion at a given frequency. The frequency of a wave refers to how often the particles of the medium vibrate when a wave passes through the medium. The frequency of a wave is measured as the number of complete back-and-forth vibrations of a particle of the medium per unit of time. If a particle of air undergoes 1000 longitudinal vibrations in 2 seconds, then the frequency of the wave would be 500 vibrations per second. A commonly used unit for frequency is the Hertz (abbreviated Hz), where 1 Hertz = 1 vibration/second.

The ears of a human (and other animals) are sensitive detectors capable of detecting the fluctuations in air pressure which impinge upon the eardrum. The human ear is capable of detecting sound waves with a wide range of frequencies, ranging between approximately 20 Hz to 20 000 Hz. Any sound with a frequency below the audible range of hearing (i.e., less than 20 Hz) is known as an infrasound and any sound with a frequency above the audible range of hearing (i.e., more than 20 000 Hz) is known as an ultrasound. Humans are not alone in their ability to detect a wide range of frequencies. Dogs can detect frequencies as low as approximately 50 Hz and as high as 45 000 Hz. Cats can detect frequencies as low as approximately 45 Hz and as high as 85 000 Hz. Bats, being nocturnal creatures, must rely on sound echolocation for navigation and hunting. Bats can detect frequencies as high as 120 000 Hz. Dolphins can detect frequencies as high as 200 000 Hz. While dogs, cats, bats, and dolphins have an unusual ability to detect ultrasound, an elephant possesses the unusual ability to detect infrasound, having an audible range from approximately 5 Hz to approximately 10 000 Hz.

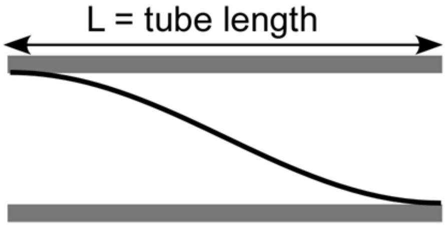
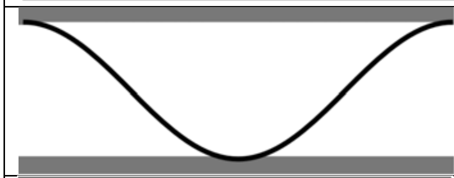
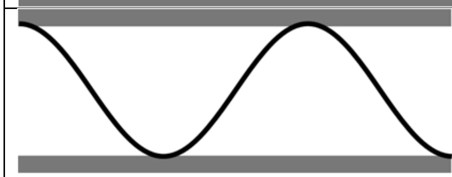
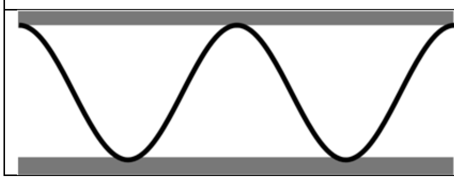
The sensation of frequencies is commonly referred to as the pitch of a sound. A high pitch sound corresponds to a high frequency sound wave and a low pitch sound corresponds to a low frequency sound wave. Amazingly, many people, especially those who have been musically trained, are capable of detecting a difference in frequency between two separate sounds which is as little as 2 Hz.

When two sound waves with slightly different frequencies superimpose, the phenomenon of beats happens. The resulting sound has a frequency equal to the difference between the frequencies of the two superimposing waves and an amplitude that changes in time.

Standing Waves in Columns of Air

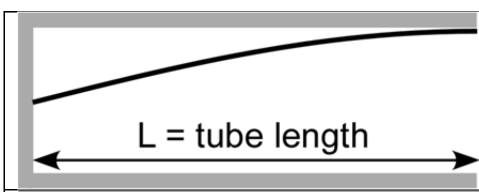
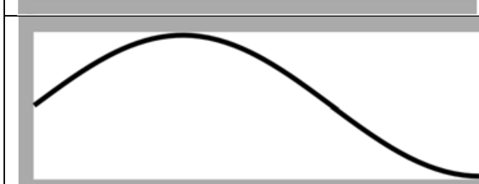
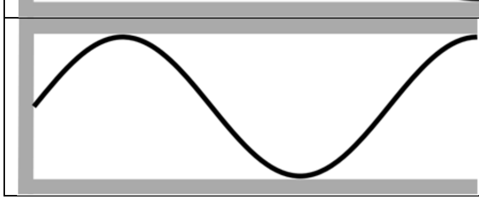
Standing longitudinal waves can be set up in a tube of air, such as a flute, or organ pipe, as the result of interference between sound waves traveling in opposite directions. The tube may be open at both ends or have one end closed. If one end is closed, a node must exist at that end because the movement of air is restricted. If the end is open, an antinode exists there because air can move freely.

Let's consider first standing waves in a tube open at both ends. Standing waves in air columns with both ends open display the same characteristics as waves on a string with both ends fixed.

	In this case, the length of the tube corresponds to half the wavelength: $L=\frac{\lambda_1}{2}\Rightarrow\lambda_1=2L$ and the wave has one node. This is the fundamental frequency or the fundamental harmonic.
	In this case, the length of the tube corresponds to the wavelength: $L=\lambda_2\Rightarrow\lambda_2=L$ and the wave has two nodes This is the second harmonic.
	In this case, the length of the tube corresponds to one and a half wavelength: $L=\frac{3}{2}\lambda_3\Rightarrow\lambda_3=\frac{2}{3}L$ and the string has three nodes. This is the third harmonic.
	In this case, the length of the tube corresponds to two wavelengths: $L=2\lambda_4\Rightarrow\lambda_4=\frac{L}{2}$ and the string has four nodes.

In general, frequencies can be determined from $f=\frac{v}{\lambda}$. Therefore the fundamental frequency will be: $f_1=\frac{v}{\lambda_1}\Rightarrow f_1=\frac{v}{2L}$. The rest of the harmonics can easily be determined by realizing that $f_n=nf_1 \text{ where } n=1,2,3,\ldots$. The harmonics in a both ends open tube are similar to the ones set up in a string fixed at both ends.

If a tube is open at one end and closed at the other, the open end is an antinode while the closed end is a node.

	In this case, the length of the tube corresponds to a quarter of the wavelength: $L=\frac{\lambda_1}{4}\Rightarrow\lambda_1=4L\Rightarrow f_1=\frac{v}{\lambda_1}=\frac{1}{4}\frac{v}{L}$
	In this case, the length of the tube corresponds to three quarters of the wavelength: $L=\frac{3\lambda_3}{4}\Rightarrow\lambda_3=\frac{4}{3}L\Rightarrow f_3=\frac{v}{\lambda_1}=\frac{3}{4}\frac{v}{L}=3f_1$
	In this case, the length of the tube corresponds to five quarters of the wavelength: $L=\frac{5\lambda_5}{4}\Rightarrow\lambda_5=\frac{4}{5}L\Rightarrow f_5=\frac{v}{\lambda_1}=\frac{5}{4}\frac{v}{L}=5f_1$

Thus in general, the frequency can be determined as: $f_n = n\frac{v}{4L} = nf_1$ where $n = 1,3,5,\ldots$

In contrast with the tube open at both ends, there are no even multiples of the fundamental harmonics for the tubes opened at one end only.

Reading Page: Light as a Wave

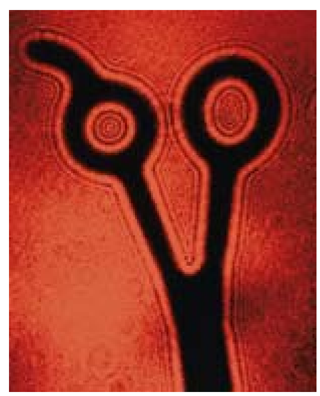
For a long time, scientists asked "Is light a wave or a stream of particles?" Experiments involving light showed that light behaves as particles in some situations and as waves in others. We will focus on the wavelike nature of light.

Light exhibits certain behaviors which are characteristic of any wave: it reflects/refracts in the same manner that any wave would. Light undergoes interference in the same manner that any wave would interfere. Light behaves in a way that is consistent with our conceptual and mathematical understanding of waves. Since light behaves like a wave, one would have good reason to believe that light is a wave. One of the behaviors of waves that we have not discussed previously is diffraction, and light diffracts in the same manner that any wave would diffract. But what is diffraction?

Reflection involves a change in direction of waves when they bounce off a barrier. Refraction/transmission involves a change in the direction of waves as they pass from one medium to another. And diffraction involves a change in direction of waves as they pass through an opening or around an obstacle in their path. Water waves have the ability to travel around corners, around obstacles and through openings, as shown in the picture below.

Sound waves do the same. You can hide behind a door and still hear what the person inside the room is saying. But what about light? Do light waves bend around obstacles and through openings? Are we able to see around corners? The obvious answer is no, we can't see around a corner but that does not mean that light does not bend around the corner. It actually does, but the bending is so small that it is not visible to our eyes.

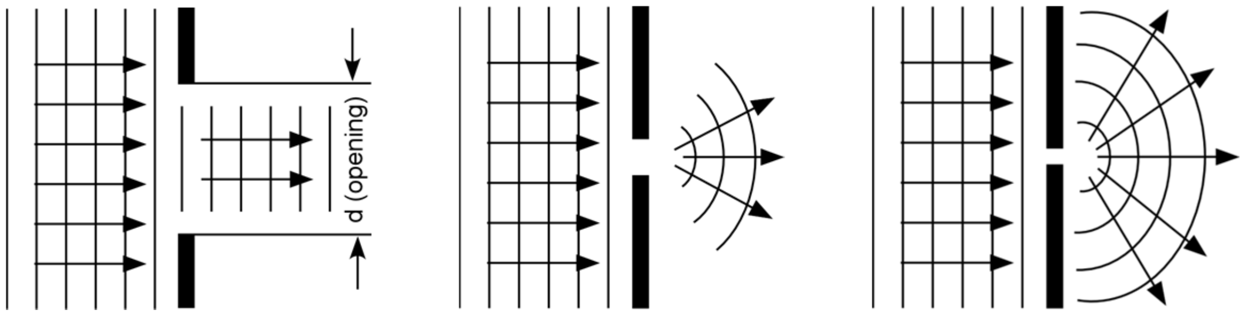
From http://commons.wikimedia.org/wiki/Image:Water_diffraction.jpg



When light encounters an obstacle in its path, the obstacle blocks the light and tends to form a shadow in the region behind the obstacle. Light does not exhibit a very noticeable ability to bend around the obstacle and fill in the region behind it with light. Nonetheless, light does diffract around obstacles. In fact, if you observe a shadow carefully, you will notice that its edges are extremely fuzzy (see above the picture of a scissor).

Interference effects occur due to the diffraction of light around different sides of the object, causing the shadow of the object to be fuzzy. This can be demonstrated with a laser and a penny. Light diffracting around the right edge of a penny can constructively and destructively interfere with light diffracting around the left edge of the penny. The result is that an interference pattern is created; the pattern consists of alternating rings of light and darkness. Such a pattern is only noticeable if a narrow beam of monochromatic light (i.e., single wavelength light) is passed directed at the penny.

Another way for waves to undergo diffraction is to pass through an opening. In order for diffraction to occur, the size of the opening must be on the same scale with the wavelength of the wave. When light passes through an opening that is large compared with the wavelength of light, it casts a shadow that looks like a sharp boundary between the light and dark areas of the shadow. But if we pass light through a thin razor slit in a piece of opaque cardboard, we see that the light diffracts. The sharp boundary between the light and dark areas disappears, and the light spreads out like a fan to produce a bright area that fades into darkness without sharp edges. The light is diffracted: the smaller the width of the slit, the wider the "fan" of light.



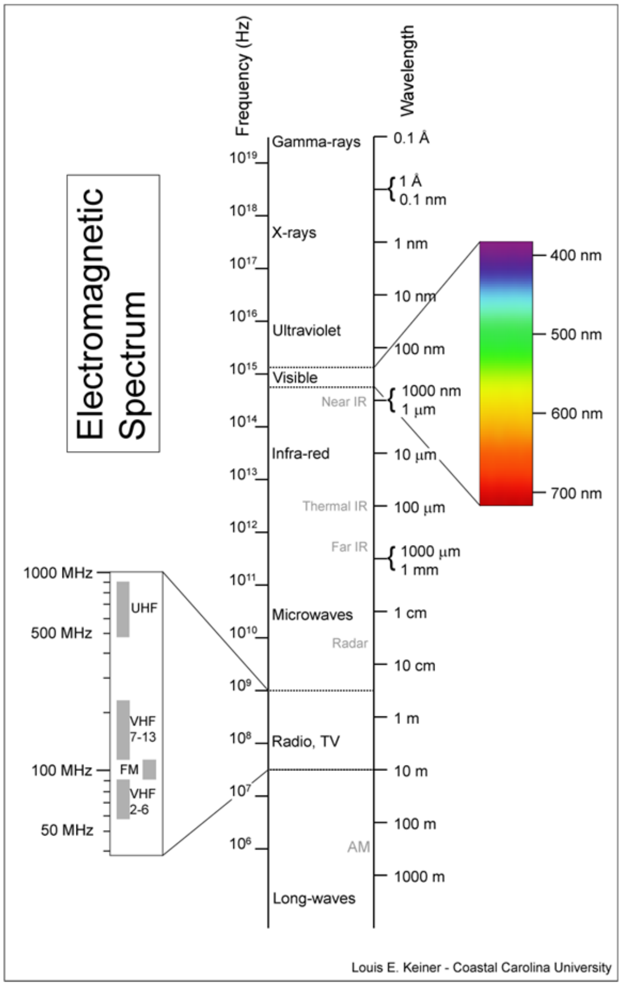
$\lambda \ll d$ $\qquad$ $\lambda = d$ $\qquad$ $\lambda \gg d$

Interesting patterns are produced when light waves diffract/interfere. For example, the beautiful colors that show up on a CD when you shine light on it, come from the diffraction of light on the many ridges that a CD has. But why do we have so many different colors? Because white light is made up of light with different wavelengths. When white light diffracts from the surface of the CD, every single color of light (having a different wavelength) will diffract at different angles. This shows us that white light is made up of a multitude of light waves of different wavelengths, with each color corresponding to a specific wavelength. The CD is what we call a diffraction grating that separates the different wavelengths of light. Another example of a common diffraction grating is the wings of a butterfly.

From http://commons.wikimedia.org/wiki/Image:Blue_morpho_butterfly.jpg

We have shown up until now that indeed light is a wave. But what is waving? For sound waves, the molecules in the air are the ones who create the sound. For a slinky, the motion of the coils creates a wave. What is light though?

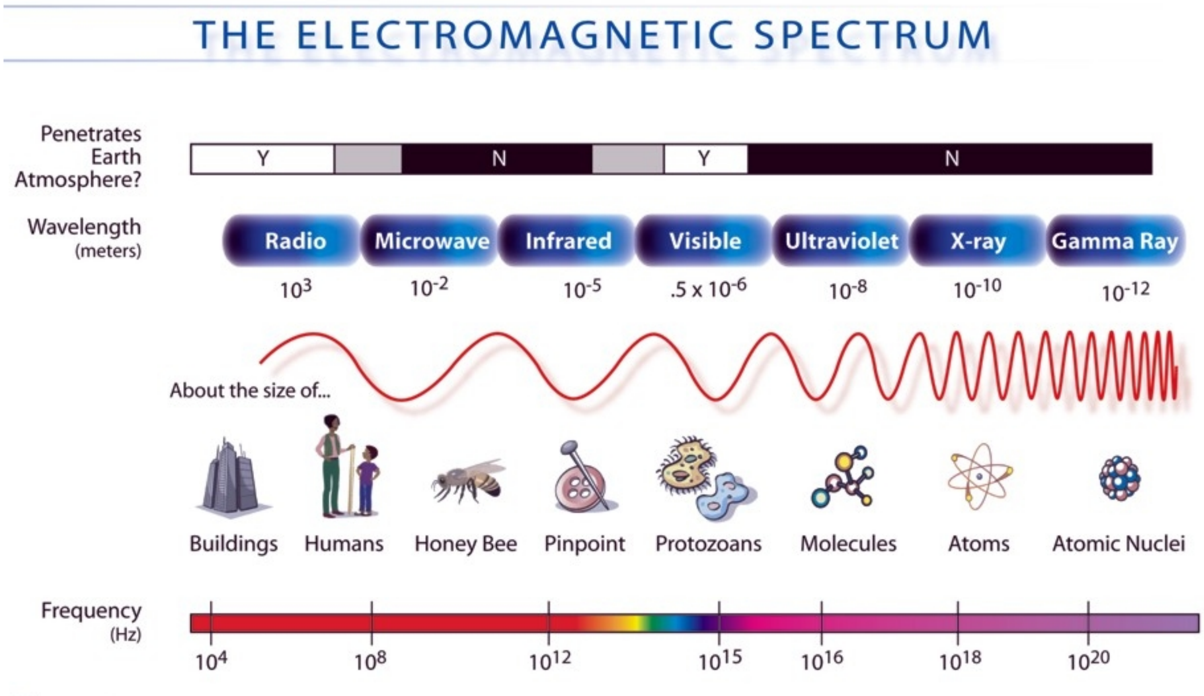
Light is an electromagnetic wave, and it is a very special type of wave because it needs no medium to propagate. Light comes to earth from the Sun even though there is nothing out there to "transfer" the motion. Electromagnetic waves are capable of transporting energy through the vacuum of outer space. Electromagnetic waves are produced by a vibrating electric charge and as such, they consist of both an electric and a magnetic component.



Electromagnetic waves exist with an enormous range of wavelengths. This continuous range of wavelengths is known as the electromagnetic spectrum. The entire range of the spectrum is often broken into specific regions. The subdividing of the entire spectrum into smaller spectra is done mostly on the basis of how each region of electromagnetic waves interacts with matter. The diagram below depicts the electromagnetic spectrum and its various regions. The longer wavelength, lower frequency regions are located on the far left of the spectrum and the shorter wavelength, higher frequency regions are on the far right. Two very narrow regions within the spectrum are the visible light region and the X-ray region.

From http://en.wikipedia.org/wiki/Electromagnetic_spectrum

Our eyes are sensitive to a very narrow band of frequencies within the enormous range of frequencies of the electromagnetic spectrum. This narrow band of frequencies is referred to as the visible light spectrum. Visible light consists of wavelengths ranging from approximately 780 nanometer (7.80×10^{-7} m) down to 390 nanometer (3.90×10^{-7} m). Specific wavelengths within the spectrum correspond to a specific color based upon how humans typically perceive light of that wavelength. The long wavelength end of the spectrum corresponds to light which is perceived by humans to be red and the short wavelength end of the spectrum corresponds to light which is perceived to be violet. Other colors within the spectrum include orange, yellow, green, blue, and indigo (ROYGBIV).



From http://en.wikipedia.org/wiki/Electromagnetic_spectrum

To explore more about light as a wave, open the simulation at:
http://phet.colorado.edu/new/simulations/sims.php?sim=Wave_Interference
and make sure you select “Light”. Using the ruler, you can measure the wavelength for different colors of light.